Int J Life Cycle Assess (2014) 19:1305–1315
DOI 10.1007/s11367-014-0731-4

A cradle-to-gate life cycle assessment of wood fibre-reinforced polylactic acid (PLA) and polylactic acid/thermoplastic starch (PLA/TPS) biocomposites

Lal Mahalle · Ayse Alemdar · Mihaela Mihai · Nathalie Legros

Received: 16 July 2013 / Accepted: 2 March 2014 / Published online: 4 April 2014

Abstract
Purpose Biopolymers are considered to be environmentally friendlier than petroleum-based polymers, but little is known about their environmental performance against petroleum-based products. This paper presents the results of a life cycle assessment (LCA) of two prototype biocomposite formulations produced by extrusion of wood fibre with either polylactic acid (PLA) or a blend of PLA and locally produced thermoplastic starch (TPS).
Methods The study followed the LCA methodology outlined in the two standards set out by the International Organization for Standardization (ISO): ISO 14040 and ISO 14044 of 2006. A life cycle inventory (LCI) for the biocomposite formulations was developed, and a contribution analysis was performed to identify the significant inputs. Environmental performances of the two formulations were then compared with each other and polypropylene (PP), a petroleum-based polymer. The US Environmental Protection Agency's impact assessment method, "TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts", was combined with Cumulative Energy Demand (a European method) in order to characterize the inventory flows. Environmental impact categories chosen for the analysis were the following: global warming, stratospheric ozone depletion, acidification of land and water, eutrophication, smog, human health (respiratory, carcinogenic, and non-carcinogenic) effects and ecotoxicity.
Results and discussion We found that PLA is the significant input which contributes mostly to fossil fuel consumption, acidification and respiratory and smog effects. Impacts from PLA transport from the faraway source significantly added more burden to its contributions. TPS causes less environmental burden compared to PLA; the environmental performance of the biocomposite improved when a blend of PLA and TPS is used in formulating the biocomposite. The two formulations performed better than PP in all the environmental impact categories except eutrophication effects, which is important on a regional basis.
Conclusions The following conclusions were drawn from this study:

- PLA is the environmentally significant input among the three raw materials.
- TPS causes less environmental burden than PLA. Environmental performance of the biocomposite improves in the life cycle energy consumption, fossil energy use, ozone depletion and non-carcinogenic impact categories when a blend of PLA and TPS is used.
- The biocomposite can outperform PP in all the impact categories except eutrophication effects if manufactured using hydroelectricity.

The biopolymer could be a potential alternative to PP as it could cause less of a burden to the environment on a cradle-to-gate basis. Environmental impacts at the complete life cycle levels should be looked into in order to fully understand its potential.

Keywords Biocomposite · Life cycle assessment (LCA) · Polylactic acid (PLA) · Prototype · Thermoplastic starch (TPS)

Responsible editor: Holger Wallbaum

L. Mahalle (✉) · A. Alemdar
FPInnovations, 2665 East Mall, Vancouver, BC V6T 1W5, Canada
e-mail: lal.mahalle@fpinnovations.ca

M. Mihai · N. Legros
NRC—National Research Council, Quebec, Canada

1 Introduction

Bioplastics are renewable, sustainable alternatives to petroleum-based plastics that solve a range of environmental problems associated with the disposal of conventional plastics and address the problem of finite oil supplies. Their market share is, however, modest due to a lack of structural integrity and their expense compared to petroleum-based polymers. Biocomposites made from bioplastics and cellulosic fibres are a relatively new class of biomaterials being developed to overcome these issues: provide acceptable product performance at competitive costs. A new prototype biocomposite from bioplastics and wood (cellulosic) fibres were developed in a collaborative project between FPInnovations and the National Research Council Canada. In this study, the biocomposites were produced by melt extrusion of polylactic acid (PLA) and blends of thermoplastic starch (TPS) and PLA with wood fibres. Due to relatively weak water and moisture absorption resistance of the PLA, interior applications such as office and institutional furniture deemed to be a potential application area for the biocomposite. Polypropylene (PP) is widely used by the furniture industry. The mechanical and physical properties of the biocomposites were assessed against PP and found that the biocomposite possesses comparable or better performances compared to PP with no additives (Mihai et al. 2011; Legros et al. 2011; Mihai et al. 2012; Mihai et al. 2013). Without any additive, the tensile strength of the wood fibre-PLA biocomposites is much higher than the neat PP (Mihai et al. 2013). In addition to mechanical properties, environmental performance is another key factor that determines the success of these biocomposites, which was the focus of this study. We evaluated process inputs and environmental performance of the two formulations, and their relative performances against PP, using the life cycle assessment (LCA) methodology.

The following goals were set to assess the cradle-to-gate environmental performance of a prototype biocomposite produced at lab scale:

- Develop life cycle inventory for the formulation 1 (30 % wood fibre+35 % PLA+35 % TPS).
- Develop life cycle inventory for the formulation 2 (30 % wood fibre+70 % PLA).
- Perform life cycle impact assessment (LCIA) to identify significant inputs within the two formulations.
- Compare and contrast environmental performances of the two formulations and with the performance of PP.

The outcomes of this study will provide important decision support information to policy makers and the prospective manufacturers in the commercialization phase of these new biocomposites on material selection options that minimize environmental impacts.

2 Methodology

The study was conducted in accordance with the four-phase LCA methodology defined in two standards set out for LCA by the International Organization for Standardization (ISO): ISO 14040 (2006) and ISO 14044 (2006). The methodology involves defining the goal and scope of the study (phase I), which is followed by an inventory analysis (phase II). In the inventory analysis, a flow model of inputs and environmental outputs are constructed to create a life cycle inventory. The inventory analysis is then followed by an impact assessment (phase III), where characterization of the inventory data (i.e. sorting and assigning flow data to specific impact categories (such as acidification, eutrophication, global warming potential effects, etc.)) is done in order to evaluate the significance of potential environmental impacts. Finally, the inventory analysis and impact assessment results are summarized in the interpretation phase (phase IV) to provide conclusions and recommendations.

2.1 Study scope

2.1.1 System boundary

The system boundaries for formulas 1 and 2 are shown in Figs. 1 and 2, respectively. The system boundary takes into account all the energy and material inputs into, and environmental outputs from, all the cradle-to-gate processes associated with the manufacturing of these biocomposites: raw material extraction, input manufacture, pre-treatment of inputs and biocomposite manufacture. The issue with the biocomposite is it is still a prototype polymer; little is known about the products that could be manufactured from it. As a result, conducting cradle-to-grave LCAs are impossible at this stage.

Wood fibre granulation and drying are the two steps involved in the pre-treatment of inputs, while manufacturing of the biocomposites can be subdivided into compounding, grinding, drying and injection molding. Landfilling is considered to be the default disposal practice of biocomposite manufacturing waste (i.e. the defective product coming out from process). The energy and material input flows occur within eastern Canada and the USA, and therefore, the geographic boundary of the study was considered as North America.

2.1.2 Functional/declared unit

In LCA, all the process inputs and environmental output flows within the system boundary are normalized based on a unit summarizing the functions of the system in order to allow for comparisons. However, in this case, the use phase and end-of-life are not included in the system boundary, and thus, the functions of the product system are not relevant to the

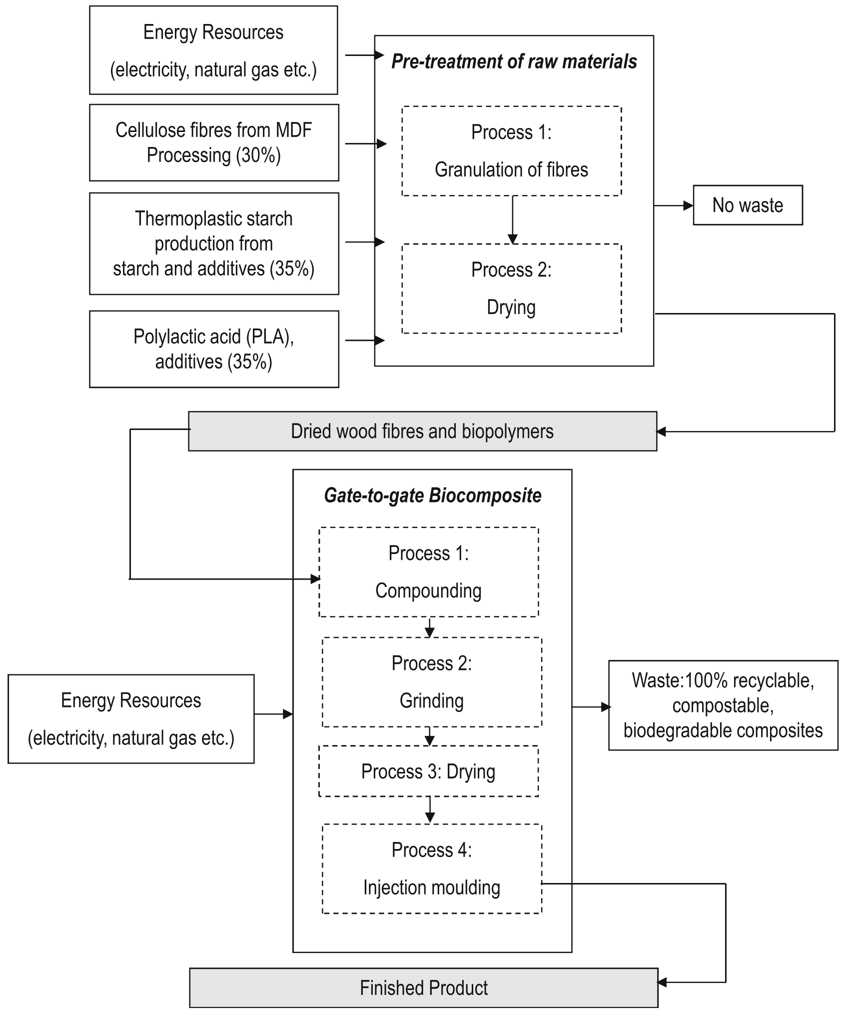

Fig. 1 System boundary for formulation 1

analysis. As a result, a declared unit based on the manufacturing output was used to normalize the flows to and from the environment. The selected declared unit was "one kilogram of output with physical and mechanical properties specified in ASTM standards for composites (i.e. ASTM D638-10, ASTM D256-10, ASTM D570-98 Reapproved 2005; ASTM D 5229/D5229M-92 Reapproved 2004; ASTM D5338-98 Reapproved 2003)".

A summary of the tested mechanical and physical properties and test results is provided in Table 1. Interior applications such as office and institutional furniture were considered to be the potential applications of this biocomposite. The biocomposite is superior to PP in the properties tested (except in the Izod impact strength which is not significant); however, to be conservative, both types were treated as having equivalent properties. This declared unit allows environmental performance comparison of the two biocomposite formulations as well as their relative environmental performances against PP for interior applications. Creep, fatigue, and low UV and fire resistance/flammability properties are common drawbacks of any thermoplastics (Sain et al. 2000; Almeras et al. 2003; Diagne et al. 2005; Butylina et al. 2012), and hence, these properties were considered to be common to both petroleum- and bio-based types in the comparison.

2.1.3 Exclusion of insignificant LCI flows

The cut-off criteria stated below provided the basis for the exclusion of the insignificant input LCI flows:

(a) Mass—if a flow is less than 1 % of the cumulative mass of the model flows, it may be excluded, providing its environmental relevance is minor.
(b) Energy—if a flow is less than 1 % of the cumulative energy of the system model, it may be excluded, providing its environmental relevance is minor.
(c) Environmental relevance—if a flow meets the above two criteria, but is determined (via secondary data analysis) to contribute 2 % or more to a product life cycle impact category, it is included within the system boundary.

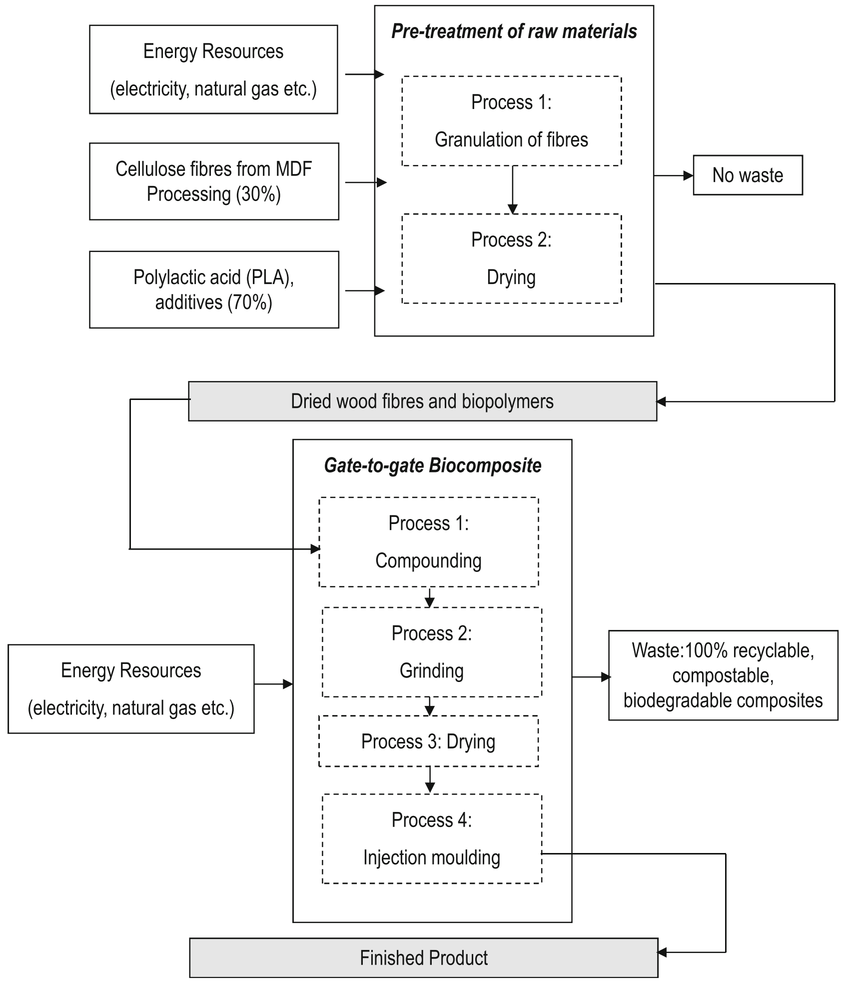

Fig. 2 System boundary for formulation 2

The environmental impacts from manufacture and installation of capital equipment and buildings have generally been shown to be minor relative to the throughput of materials and components over the useful lives of the buildings and equipment; the capital infrastructure was also excluded from the system boundary.

2.1.4 Allocation of environmental impacts

This biocomposite manufacture is a single output process, which is composed of 98 % of the product that meets the specified properties (called “main product”), and 2 % of defective product considered as waste. This waste can either be internally recycled

Table 1 Summary results of the tested physical properties

Property	Formulation 1	Formulation 2	Polypropylene
Density (g/cm^3)	1.36	1.29	0.90
Tensile strength (MPa) ASTM D638-10	56.3	72.7	34
Tensile Modulus (GPa) ASTM D638-10	5.8	6.6	1.5
Izod impact strength (kJ/m^2)	1.6	2.4	3.2
Moisture and water absorption ASTM D 5229/D5229M-92 (Reapproved 2004) ASTM D570-98 (Reapproved 2005)	Poor	Poor/medium	Good
Biodegradability/compostability at 58 °C, 65 %, 60 days ASTM D5338-98 (Reapproved 2003)	Yes	Yes	No

within the system or disposed in a landfill. ISO states that environmental burden of a product system should not be allocated to a waste; the environmental burden of the biocomposite manufacture was entirely allocated to the main product.

However, among the process inputs, wood fibre inputs to the biocomposite manufacture is a multistep process. The study used the secondary LCI data compiled by the Athena (2009a) Institute for softwood fibre which allocates its environmental impacts based on the economic values of sawn lumber and its co-products. The study used the same allocation principles and factors in drawing that data.

2.1.5 Data and initial data quality requirements

Firsthand data for energy consumption were gathered for lab-scale production of the two biocomposite formulations. The study also requires background LCI data for all the energy and material inputs that are used in these processes in modelling their environmental impacts. Only critically reviewed data were used for the secondary data sources. These data were assured to be representative of North America in terms of the geographic and technological coverage and of a recent vintage, i.e. less than 10 years old.

2.1.6 Background data sources for energy and ancillary material inputs

The study relied mainly on two LCI data sources in modelling the environmental impacts of the energy and material inputs used in the manufacture of the biocomposites: the US LCI database (www.nrel.gov/lci) and US-EI database (http://www.earthshift.com/US-EI%20library.pdf). The US-EI database has been created by filling the data gaps in the US LCI database with ecoinvent data. European electricity has been replaced with US electricity in using ecoinvent data to fill the data gaps. Wherever applicable, the electricity grids of the secondary LCI data were replaced with Quebec electricity grids available in the Athena electricity data for Canadian provinces in order to make that data more representative to the circumstances in Quebec. The secondary LCI data sources used to model the material and energy inputs for the lab-scale manufacture are shown in Table 2.

According to Skog (2008), about 23 % of solid wood decomposes in landfills. This recent estimate was used together with the carbon content of the material inputs in order to estimate the potential greenhouse gas (GHG) emissions (carbon dioxide and methane) from decaying biocomposite manufacturing waste in landfills.

2.1.7 Selected impact assessment methods

While considering the North American focus of the study, the US Environmental Protection Agency's TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) life cycle impact assessment (LCIA) method was used for the life cycle environmental impact comparison of the two formulations. The following environmental impact categories available in TRACI method were used for this comparative assertion:

- Climate change (greenhouse gases)
- Depletion of the stratospheric ozone layer
- Acidification of land and water sources
- Eutrophication
- Formation of tropospheric ozone (photochemical oxidants)
- Human health impacts—respiratory, carcinogenic and non-carcinogenic effects
- Ecotoxicity

TRACI does not address carbon uptake by plants; carbon dioxide from air was added as a negative emission to include carbon sequestered in the plant-based material inputs such as wood fibre, PLA and TPS. In addition, total primary consumption and non-renewable fossil fuel use were included in the assessment by combining TRACI with the European-based "Cumulative Energy Demand" (CED), an impact assessment method that calculates primary energy demand (e.g. non-renewable fossil fuel, renewable biofuel, wind, hydro, etc.) of the two formulations.

3 Results

3.1 Inventory analysis

Table 3 presents the LCI flows for the manufacture of the two biocomposite formulations at the laboratory scale. The difference between the two formulations is that PLA and TPS blend is used as bioplastic matrices in formulation 1, while formulation 2 contained PLA matrix. Addition of the wood fibres (30 wt.%) improved the performance of the biopolymers; no additives (coupling agent, compatibilizer, etc.) were added to the formulations. These biocomposites consume about 31 MJ of energy in total for the laboratory-scale manufacture that was met from the provincial electricity grid in Quebec which is mostly composed of hydropower. Among the processes involved in the manufacture, compounding is the most energy intensive process as it consumes about 66 % (5.59/8.57) of the total energy demand. Electricity has been used for both raw material processing and compounded material drying that required heat energy, which could have otherwise been met from sources like steam. Pre-steaming of wood chips prior to grinding consumes a minor amount of steam, so it was not taken into account for creating this inventory. As stated earlier, this is a single output process,

Table 2 Secondary LCI data sources

Input/process		Data sources	Comments
Wood fibre		Athena LCA reports on Canadian softwood lumber and MDF and in-house data on hardwood lumber (Athena 2009a, b)	Most recent representative data
PLA		US-EI	Representative data
TPS	Maize starch	US-EI	Electricity grids changed to represent circumstances in Quebec
	Glycerin	US-EI	Electricity grids changed to represent circumstances in Quebec
Electricity		Athena electricity data	Representative data
Landfilling		US-EI	Electricity grids changed to represent circumstances in Quebec
Material transport		US-EI	North American truck transport data

but it generates about 2 % of defective product, which is waste that could either be disposed of or recycled internally. There could be fugitive emissions from material processing, compounding and drying, which were not tracked during the lab-scale manufacture.

Material transport includes transport of raw materials to the facility and waste to a landfill. The transport distances are shown in Table 4. NatureWorks LLC was the supplier of PLA, and the distance from its manufacturing facility located in Nebraska, US to Quebec was taken into account in modelling the environmental impacts of raw material transportation. Maize starch and glycerin were assumed to be received from local suppliers in Montreal. The distance from Boucherville, Quebec to a nearby landfill (e.g. Lachenaie Landfill in Terrebonne, Quebec) was used to model waste delivery to a landfill. Diesel combination trucks were the mode of transport used in creating models as it is the common mode of road transport used for bulk transport of materials.

Table 3 LCI flows for the manufacture of the two biocomposite formulations

Input			Unit	Quantity per declared unit (1 kg of biocomposite)	
				Formulation 1	Formulation 2
Materials					
Wood fibre (with 5–8 % moisture content)			kg	0.30	0.30
PLA			kg	0.35	0.70
TPS			kg	0.35	–
Energy[a]					
Electricity	Raw material processing				
		MDF fibre preparation	kWh	0.075 (0.27)	0.075 (0.27)
		Fibre granulation	kWh	0.11 (0.40)	0.11 (0.40)
		Drying	kWh	0.67 (2.41)	0.67 (2.41)
		Total	kWh	0.78 (2.81)	0.78 (2.81)
	Biocomposite manufacture				
		Compounding	kWh	5.59 (20.12)	5.59 (20.12)
		Grinding	kWh	0.25 (0.90)	0.25 (0.90)
		Drying	kWh	0.52 (1.87)	0.52 (1.87)
		Injection molding	kWh	1.35 (4.86)	1.35 (4.86)
		Total	kWh	7.71 (27.75)	7.71 (27.75)
Total energy			kWh	8.57 (30.85)	8.57 (30.85)
Emissions					
Solid waste			kg	0.02	0.02

[a] Energy consumption in MJ is shown in parentheses

Table 4 Raw material and waste transportation distances

Input/waste	Unit	Distance
Wood fibre (MDF)	km	260[a]
PLA	km	2,100
Maize starch	km	10
Glycerin	km	10
Waste (defective product)	km	32

[a] Source: Athena Institute 2009b

3.2 Life cycle impact assessment

3.2.1 Contribution analysis

LCIA results of the contribution analysis performed for formulations 1 and 2 are shown in Tables 5 and 6, respectively.

Formulation 1 uses about 65 MJ of total energy per kilogram of biocomposite on a life cycle basis. Approximately 50 % of this energy is used during gate-to-gate biocomposite production processes: 5 % for the processing of raw material entering the production and 45 % for the biocomposite manufacture. Upstream input production processes consume most of the remaining 50 % of energy: 33 and 15 % for PLA and TPS, respectively. Energy consumption for input delivery to the biocomposite manufacturing facility is minor; however, PLA delivery from the faraway source was found to be significantly contributing to global warming, acidification and smog effects. Upstream PLA production causes more eutrophication, carcinogenic and non-carcinogenic impacts, and much higher ozone depletion effects than TPS, while TPS accounts for about one-half of the acidification, respiratory, ecotoxicity and smog impacts. The electricity use for biocomposite manufacture causes significant global warming impacts, but its contributions to other environmental impacts were found to be minor. The carbon sequestered in the bio-based material inputs (wood fibre, PLA and TPS) exceeds their GHG emissions from manufacturing processes; the net CO_2 impacts become negative numbers. The impact contributions from wood fibre production and landfilling of manufacturing waste are minor.

Formulation 2 consumes approximately 78 MJ of energy per kilogram of biocomposite on a life cycle basis. PLA consumes more than 55 % of this energy for its upstream production, while biocomposite manufacture accounts for about 37 % of this total energy use. Energy consumption during wood fibre manufacturing, transport and landfilling are minor. Long-distance transport of PLA from its faraway source mostly contributes to global warming and causes significant impacts in acidification, respiratory and smog impact categories as well. Contributions from wood fibre were minor. Landfilling of the biocomposite manufacturing waste contributed considerably towards global warming and non-carcinogenic effects.

3.2.2 Comparative LCIA of the two biocomposite formulations

Results of the comparative LCIA performed for the two biocomposite formulations are presented in Fig. 3. Formulation 1 shows better environmental performance in terms of energy consumption, ozone depletion and non-carcinogenic impacts.

Table 5 Results of contribution analysis performed for biocomposite formulation 1—per kilogram of biocomposite

Impact category	Unit	Total impact	Contribution %								
			Wood fibre	PLA	TPS	Input transport			Electricity—input processing	Electricity—biocomposite manufacture	Landfilling
						PLA	TPS	Wood fibre			
Global warming	kg CO2 eq	−0.41	−144.41	−5.13	9.80	17.11	<1	1.94	1.12	10.93	8.56
Acidification	H+ moles eq	0.36	1.26	35.26	52.38	6.37	<1	<1	<1	3.58	<1
Carcinogenic	kg benzen eq	1.15E-03	<1	59.74	27.48	1.99	<1	<1	<1	3.44	6.46
Non-carcinogenic	kg toluen eq	10.50	<1	39.39	27.77	4.57	<1	<1	<1	4.07	22.59
Respiratory effects	kg PM2.5 eq	6.68E-04	<1	36.81	52.96	3.96	<1	<1	<1	4.39	<1
Eutrophication	kg N eq	9.20E-03	<1	58.38	40.65	0.24	<1	<1	<1	<1	<1
Ozone depletion	kg CFC-11 eq	1.04E-07	<1	81.90	18.05	0.00	<1	<1	<1	<1	<1
Ecotoxicity	kg 2,4-D eq	0.43	<1	39.64	52.60	3.11	<1	<1	<1	3.41	<1
Smog	g NOx eq	3.40E-03	2.76	27.38	50.78	14.11	<1	1.60	<1	2.85	<1
Total energy	MJ eq	65.47	<1	33.24	15.01	1.45	<1	<1	4.61	44.83	<1
Non-renewable, fossil	MJ eq	16.93	<1	59.57	29.26	5.60	<1	<1	<1	3.86	<1
Non-renewable, nuclear	MJ eq	0.18	<1	79.30	20.60	<1	<1	<1	<1	<1	<1
Renewable, biomass	MJ eq	13.37	<1	65.50	34.40	<1	<1	<1	<1	<1	<1
Renewable, other	MJ eq	34.99	<1	7.93	0.68	<1	<1	<1	8.44	82.01	<1

Table 6 Results of contribution analysis performed for biocomposite formulation 2—per kilogram of biocomposite

Impact category	Unit	Total impact	Contribution %						
			Wood fibre	PLA	Input transport		Electricity—input processing	Electricity—biocomposite manufacturing	Landfilling
					PLA	Wood fibre			
Global warming	kg CO2 eq	−0.41	−145.04	−10.32	34.40	1.95	1.13	10.99	6.89
Acidification	H+ moles eq	0.32	1.52	78.96	14.27	<1	<1	4.01	<1
Carcinogenic	kg benzen eq	1.54E-03	<1	89.03	2.96	<1	<1	2.56	4.82
Non-carcinogenic	kg toluen eq	12.18	<1	67.90	7.88	<1	<1	3.51	19.47
Respiratory effects	kg PM2.5 eq	5.87E-04	1.16	83.78	9.02	<1	<1	4.99	<1
Eutrophication	kg N eq	1.09E-02	<1	98.97	0.41	<1	<1	<1	<1
Ozone depletion	kg CFC-11 eq	1.70E-07	<1	99.97	<1	<1	<1	<1	<1
Ecotoxicity	kg 2,4-D eq	0.39	<1	87.96	6.90	<1	<1	3.79	<1
Smog	g NOx eq	3.09E-03	3.28	60.28	31.07	1.76	<1	3.14	<1
Total energy	MJ eq	78.38	<1	55.52	2.42	<1	3.85	37.44	<1
Fossil	MJ eq	23.01	<1	87.64	8.24	0.47	<1	2.84	<1
Nuclear	MJ eq	0.29	<1	99.93	<1	<1	<1	<1	<1
Biomass	MJ eq	17.52	<1	99.92	<1	<1	<1	<1	<1
Renewable, other	MJ eq	37.55	<1	14.78	<1	<1	7.86	76.40	<1

Formulation 2 consumes about 13 MJ more total energy and 6 MJ of non-renewable fossil fuel than formulation 2 on a life cycle basis. Both formulations had the same amount of net carbon benefits when accounting for the amount of carbon sequestered in the plant-based material inputs, i.e. wood fibre, PLA and TPS. Eutrophication, acidification, carcinogenic, respiratory, ecotoxicity and smog impacts of the two formulations were more or less the same.

3.2.3 Environmental performance against petroleum-based polymers

Life cycle environmental performances of the biocomposite were compared with the petroleum-based plastic data available in the US-EI database for PP. LCIA results of the two biocomposite formulations against petroleum-based plastics are shown in Table 7 and Fig. 4 on an absolute and percentage basis, respectively. PP consumes significantly higher amounts of energy than the biocomposite formulation 1. On a life cycle basis, about 56 to 62 MJ of non-renewable fossil energy can be displaced by substituting biocomposites for petroleum-based plastics if manufactured using hydroelectricity. The biocomposite also performed better than polypropylene in all the environmental impact categories except eutrophication effects.

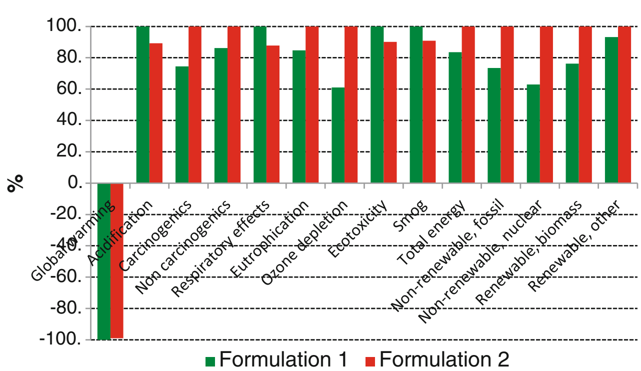

Fig. 3 Comparative LCIA results of the two formations on a percentage basis

4 Interpretation of results

The significant inputs and processes found in contribution analysis were further assessed to identify ways to improve the performance of the PLA- and PLA/TPS-based biocomposites. In addition, environmental performances of the two formulations are reevaluated against the potential alternative energy sources that could be used during biocomposite manufacture and internal recycling of manufacturing waste. Finally, uncertainties surrounding the missing data and scale of manufacture are discussed to provide context to the conclusions and recommendations.

4.1 Significant process inputs

The only difference between the two biocomposite formulations is that formulation 1 uses both PLA and TPS as

Table 7 Environmental performance of the two biocomposite formulations against polypropylene—absolute values per declared/FU

Impact category	Unit	Biocomposite formulation 1	Biocomposite formulation 2	Polypropylene
Global warming	kg CO2 eq	−0.41	−0.41	1.45
Acidification	H+ moles eq	0.36	0.32	1.50
Carcinogenic	kg benzen eq	1.15E-03	1.54E-03	1.07E-02
Non-carcinogenic	kg toluen eq	10.50	12.18	325.01
Respiratory effects	kg PM2.5 eq	6.68E-04	5.87E-04	6.39E-03
Eutrophication	kg N eq	9.20E-03	1.09E-02	6.06E-04
Ozone depletion	kg CFC-11 eq	1.04E-07	1.70E-07	2.20E-07
Ecotoxicity	kg 2,4-D eq	0.43	0.39	2.83
Smog	g NOx eq	3.40E-03	3.09E-03	3.95E-03
Total energy	MJ eq	65.47	78.38	78.79
Non-renewable, fossil	MJ eq	16.93	23.01	78.61
Non-renewable, nuclear	MJ eq	0.18	0.29	0.05
Renewable, biomass	MJ eq	13.37	17.52	0.01
Renewable, other	MJ eq	34.99	37.55	0.12

bioplastic matrices while formulation 2 relies only on PLA. PLA, as revealed in the contribution analysis, is the most significant input in terms of environmental burden, and its long-distance transport from the source causes more environmental burden in the two impact categories of highest concern (i.e. global warming and ozone depletion) than formulation 2. Combining PLA together with TPS (a locally available polymer source) enables improvement of the life cycle environmental performance of the biocomposites in these two most important impact categories.

In addition, the Quebec electricity is mostly generated from hydropower and might have being a factor that influenced the comparative performance of the biocomposite against PP. The uncertainty surrounding the type of electricity grid used was tested using the same US grid that is used for PP manufacturing that relies mostly on coal. Significant performance decreases of the biocomposite occur in most of the considered impact categories, and hence, the findings are valid if the

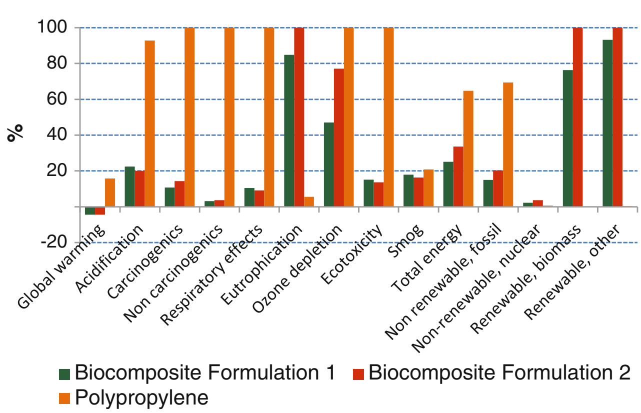

Fig. 4 Environmental performance of the two biocomposite formulations against polypropylene on a percentage basis

biocomposite is manufactured using a grid that relies on hydroelectricity (see Table 9).

4.2 Performance against recycling of manufacturing waste

Sensitivity of the LCIA results was tested against recycling of defective products through reprocessing to produce biocomposite within the same system against landfilling. The sensitivity analysis results are shown against the base case in Table 8. Some performance improvement can be obtained in terms of total primary energy use and environmental impacts by reprocessing manufacturing waste within the system. Manufacturing waste could also be recycled externally through incineration for energy. Incineration of municipal solid waste including wood prevents methane emissions from landfilling and, thus, reduces contributions to global warming (global warming potential of methane is 25 times higher than carbon dioxide) but performs poorly in other environmental impact categories such as acidification and eutrophication (Assamoi and Lawryshyn 2012). A sensitivity analysis on the performance against incineration was, however, not tested since there is no existing emission data for the incineration of this biocomposite.

4.3 Uncertainty surrounding missing data and scale of manufacture

Steam consumption during wood fibre processing and processing emissions (i.e. volatile organic compounds or VOCs) from biocomposite manufacture had not been tracked; this data was not available for this LCA. Steam is used in very small quantities for fibre processing. Both formulations use the same amount of wood fibre; their steam consumption for wood fibre processing would be the same. As a result, the

Table 8 Environmental performance against reprocessing of defective products within the system

Impact category	Unit	Formulation 1		Formulation 2	
		Base case	Sensitivity	Base case	Sensitivity
Global warming	kg CO2 eq	−0.41	−0.43	−0.41	−0.42
Acidification	H+ moles eq	0.36	0.36	0.32	0.32
Carcinogenic	kg benzen eq	1.15E-03	1.05E-03	1.54E-03	1.44E-03
Non-carcinogenic	kg toluen eq	10.50	7.98	12.18	9.62
Respiratory effects	kg PM2.5 eq	6.68E-04	6.56E-04	5.87E-04	5.76E-04
Eutrophication	kg N eq	9.20E-03	8.96E-03	1.09E-02	1.06E-02
Ozone depletion	kg CFC-11 eq	1.04E-07	1.02E-07	1.70E-07	1.66E-07
Ecotoxicity	kg 2,4-D eq	0.43	0.42	0.39	0.38
Smog	kg NOx eq	3.40E-03	3.33E-03	3.09E-03	3.02E-03
Total energy	MJ eq	65.47	64.76	78.38	77.42
Non-renewable, fossil	MJ eq	16.93	16.61	23.01	22.57
Non-renewable, nuclear	MJ eq	0.18	0.18	0.29	0.29
Renewable, biomass	MJ eq	13.37	13.10	17.52	17.18
Renewable, other	MJ eq	34.99	34.87	37.55	37.38

uncertainty surrounding this missing data would be cancelled out in the comparison of the two formulations.

VOC emissions from PLA manufacturing available in the US-EI database were used as proxy data to assess the sensitivity of the findings against missing biocomposite processing emissions data; the effect of this missing data was found to be minor (see Table 9).

Another uncertainty is the scale of the manufacturing. This LCA was conducted for a prototype product manufactured at the lab scale: the energy consumption and associated environmental burden could go down, while some extra energy would be needed for internal handling of bulk raw materials during commercial large-scale manufacturing. The environmental performance of the two formulations could change as a result of changes in energy use; however, final outcome of the comparison might be the same with large-scale manufacture.

5 Conclusions

The following conclusions were drawn from this study:

- Among the three material inputs (wood fibre, PLA and TPS) to the biocomposite manufacturing process, PLA is

Table 9 Electricity grid and process emission sensitivity results of the biocomposite against the base case

Impact category	Unit	Base case		Electric grid sensitivity		Process emissions (VoC) sensitivity	
		Formulation 1	Formulation 2	Formulation 1	Formulation 2	Formulation 1	Formulation 2
Global warming	kg CO2 eq	−0.41	−0.41	6.57	6.57	−0.41	−0.41
Acidification	H+ moles eq	0.36	0.32	3.43	3.39	0.36	0.32
Carcinogenic	kg benzen eq	1.15E-03	1.54E-03	0.05	0.05	1.15E-03	1.54E-03
Non-carcinogenic	kg toluen eq	10.50	12.18	1,554.77	1,556.45	10.50	12.18
Respiratory effects	kg PM2.5 eq	6.68E-04	5.87E-04	0.01	0.01	6.68E-04	5.87E-04
Eutrophication	kg N eq	9.20E-03	1.09E-02	0.01	0.01	9.20E-03	1.09E-02
Ozone depletion	kg CFC-11 eq	1.04E-07	1.70E-07	1.56E-07	2.23E-07	1.04E-07	1.70E-07
Ecotoxicity	kg 2,4-D eq	0.43	0.39	7.72	7.68	0.43	0.39
Smog	g NOx eq	3.40E-03	3.09E-03	0.03	0.03	5.36E-03	5.05E-03
Total energy	MJ eq	65.47	78.38	133.82	146.73	65.47	78.38
Non-renewable, fossil	MJ eq	16.93	23.01	114.59	120.68	16.93	23.01
Non-renewable, nuclear	MJ eq	0.18	0.29	0.66	0.77	0.18	0.29
Renewable, biomass	MJ eq	13.37	17.52	13.62	17.78	13.37	17.52
Renewable, other	MJ eq	34.99	37.55	4.94	7.50	34.99	37.55

found to be the significant input. Its contributions become worse when accounting for PLA import from its faraway source.

- TPS causes less environmental burden than PLA, and the environmental performance of the biocomposite can be improved by substituting locally available TPS for PLA.
- Reprocessing manufacturing waste within the system helps improve the environmental performance of the biocomposite.
- This LCA is based on a prototype product manufactured at the lab scale. Its energy use may go down with the large-scale manufacture while some energy is expected to be used for internal bulk material handling within the manufacturing facility.
- Formulation 1 shows better environmental performance in terms of life cycle energy consumption, fossil energy use, ozone depletion and non-carcinogenic impacts than formulation 2 as the former uses both PLA and TPS. The biocomposite outperforms PP in all the impact categories except eutrophication effects if manufactured using hydroelectricity.

In general, formulation 1 performs better in terms of life cycle energy and non-renewable fossil energy use than formulation 2. Also, it outperforms PP in energy consumption and the two environmental impact categories of highest concern (global warming and ozone depletion) and, hence, can be recommended for future product screening and commercialization. The findings are more or less consistent with existing literature on comparative assessment of bio-based polymers made with PLA against petroleum-based alternatives such as PP: the study conducted by Hermann et al. (2010) found that bio-based wrappings manufactured using PLA performed better in the environment, particularly in the global warming impact category, than PP, for example.

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